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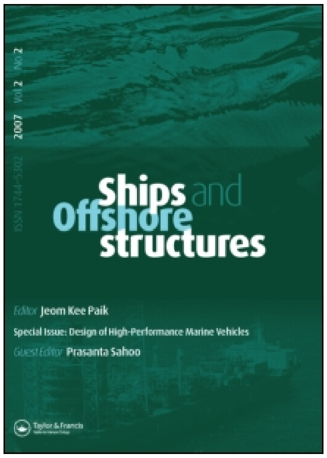

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A case study: theoretical and experimental analysis of motion characteristics of a trimaran hull form

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A case study: theoretical and experimental analysis of motion characteristics of a trimaran hull form*

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Abstract: Vessel motion is an aspect of design that requires a high degree of consideration with regard to passenger comfort. Within the last two decades, extensive research work has resulted in development of numerical and analytical methods for the prediction of heave and pitch motions of catamaran hull forms. However, in the recent past, there appears to be a strong interest in the development of trimaran hull forms. Investigations have shown that little research has been conducted on such hull forms to reduce their motions in heave and pitch. In this article, we investigate the effects of the (longitudinal) stagger of the sidehulls on the motions in heave and pitch of a representative trimaran hull. To quantify the effects of longitudinal stagger of the sidehulls (outriggers) with respect to the centrehull, experimental investigations were undertaken at the Australian Maritime College Ship Hydrodynamic Centre. A round-bilge high-speed hull form model of the Australian Maritime Engineering CRC systematic series was constructed and subjected to extensive experimental analysis as well as computer simulations (HYDROS) for four different longitudinal stagger positions. The investigations demonstrated that this variation and the resulting variation in the radius of gyration could have a significant effect on the heave and pitch motions. The literature survey indicated that, to date, investigations on trimaran hull forms have been confined to determining the effects of transverse and longitudinal positions of the sidehulls only on the resistance characteristics. The investigations undertaken within the scope of this article provide a starting point to investigate the effect of the trimaran's sidehull position on the motions of the vessel.

Key words: Motion characteristics, trimaran hull form.

NOTATION

A_0	Wave amplitude
A_3	Heave amplitude
A_5	Pitch amplitude in radians
B_1	Beam of centrehull
B_2	Beam of outrigger
C_B	Block coefficient
C_M	Midship section coefficient
C_P	Prismatic coefficient
C_{WP}	Waterplane-area coefficient
g	Gravitational constant
k_0	Wave number, $2\pi / L_W$
L	Waterline length of vessel
L_1	Waterline length of centrehull
L_2	Waterline length of outrigger
r_2	Longitudinal stagger of outriggers
s	Separation between centreplanes of outriggers
T_1	Draft of centrehull
Δ_1	Displacement of centrehull
ω	Encounter radian frequency
∇_1	Volume of centrehull

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INTRODUCTION

Within the marine industry, the trend towards larger high-speed vessels, in conjunction with widely available modern production technologies, has led to increasing utilisation of

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trimaran hull forms. There is, however, a limited amount of research data available that focuses on the seakeeping aspects of this relatively new concept. This article constitutes a focus on the effect of the longitudinal position of the sidehulls (outriggers) on the wave-induced motion characteristics of a trimaran hull form. We also present here a comparison of the results of more than 400 experimental model test runs with a theoretical approach using HYDROS.

The comparison between the model tests and the theoretical results has been conducted with the intent of validating the theoretical capacity of this software to predict the motion characteristics of trimaran hull forms over a range of wave frequencies and Froude numbers.

LITERATURE REVIEW

Sahoo and Doctors (2004) have provided a comprehensive literature review spanning over three decades on motion characteristics of catamaran hull forms. They have presented results for heave and pitch motions in head seas for typical catamaran hull forms used in the high-speed ferry industry around the world. Theoretical results were obtained from the strip-theory method used by the computer program SEAKEEPER (2003) and HYDROS, a program that encompasses more accurately hull form section calculations.

Close correlation was demonstrated for the non-dimensional heave and pitch responses between the two methods. These results were validated by experimental work carried out at the Australian Maritime College Ship Hydrodynamic Centre on a typical catamaran hull form. It was shown that the trends predicted by SEAKEEPER (2003) and HYDROS are quite consistent with experimental results. However, HYDROS tended to correlate considerably better with experimental results than SEAKEEPER (2003).

The authors acknowledge that for a practising naval architect, strip-theory predictions for motions used by SEAKEEPER (2003) would be sufficient for initial motion predictions at Froude numbers less than 0.5. However, predictions of the peak resonant responses were generally too high by at least a factor of 2.0. Motions predicted by HYDROS suggested that it is better than SEAKEEPER (2003) at both the lower and higher Froude numbers of interest.

McGoldrick (2002) attempted to develop a relationship between the main parameters of catamaran hull forms and the resulting vessel response in heave and pitch in an irregular seaway. The calculations used were based on slender-body theory, in which the basic assumptions of strip theory used by the computer program SEAKEEPER (2003) were used to determine the added mass and damping and restoring coefficients. The results obtained were validated through experimental work undertaken at the Australian Maritime College Ship Hydrodynamic Centre. A regression analysis was performed on the results from the theoretical calculations, which could then be used for motion analysis of catamaran hull forms in the initial design stage.

Ballantyne (2005) conducted research to analyse the effects of altering the separation of the LCB and the LCF (LCF = longitudinal centre of flotation, LCB = longitudinal centre of buoyancy) on wave-induced motions of semi-SWATH hull forms. Furthermore, the effect of the radius of gyration on the heave and pitch motions was also reviewed. A systematic series of three hull forms was derived from a parent hull form using a predetermined shift in an underwater appendage to create a range of separations between the LCB and LCF. These three hulls were then subjected to experimental and theoretical analysis.

The models were tested against full-scale wave encounter frequencies between 0.1 and 0.9 Hz and for Froude numbers between 0.33 and 1.0. All Froude numbers and wave frequencies were tested at two wave heights, corresponding to full-scale wave heights of 0.5 and 1.0 m. From the study, it was found that the response amplitude operator (RAO) curves for heave and pitch decreased as the LCB–LCF separation increased at Froude numbers of 0.66 and 1.00. On the other hand, at a Froude number of 0.33, the reverse behaviour was experienced. That is, in the latter case, the pitch magnitudes decreased as the LCB–LCF separation decreased.

The theoretical investigations showed that any separation between the LCB and LCF, resulting in an increased longitudinal radius of gyration, produced lower heave and pitch natural frequencies. Results obtained from the theoretical prediction tool SEAKEEPER (2003), based on strip theory, were found to correlate reasonably well with those obtained experimentally at lower Froude numbers. However, at higher Froude numbers, overestimations in the predictions of the responses were noticed. Sahoo and Doctors (2004) have already arrived at this conclusion.

The authors note that little work has been carried out in the area of seakeeping of trimarans. The literature on the motions of multihulls is generally confined to catamarans. Moreover, the relevance of catamarans to this article on trimarans is that the hydrodynamic interference effects between the sidehulls and the centrehull are physically similar. Consequently, the same software can be used.

EXPERIMENTAL WORK

Trimaran model

The trimaran model consists of a single hull form with scaled-down sidehulls. The centrehull is of round-bilge design, with a transom stern designed for operation as a high-speed displacement hull form. The model was based on Model 9 of the Australian Maritime Engineering CRC systematic series. The geometrically scaled ratio between sidehull and centrehull is 0.459. The lines plan of Model 9 and relevant model particulars are shown in Figure 1 and Table 1, respectively. Details of the experimental work

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Table 1 **Particulars of AMECRC Monohull Model 9**

Item	Symbol	Value
Displacement mass (kg)	Δ_1	12.801
Waterline length (m)	L_1	1.596
Waterline beam (m)	B_1	0.2002
Draft (m)	T_1	0.08046
Waterplane-area coefficient	C_{WP}	0.7958
Maximum section coefficient	C_M	0.7996
Block coefficient	C_B	0.4990
Prismatic coefficient	C_P	0.6240
Slenderness coefficient	$L_1/\nabla_1^{1/3}$	6.817

Table 2 **Details of model experiments**

Item	Symbol	Value
Sidehull scale	L_2/L_1	0.4590
Sidehull stagger	r_2/L_1	0.0, −0.1, −0.2, −0.3
Sidehull spacing	s/L_1	0.4
Froude number	F_1	0.3, 0.4, 0.5, 0.6
Wave amplitude	A_0/L_1	0.00625, 0.0125

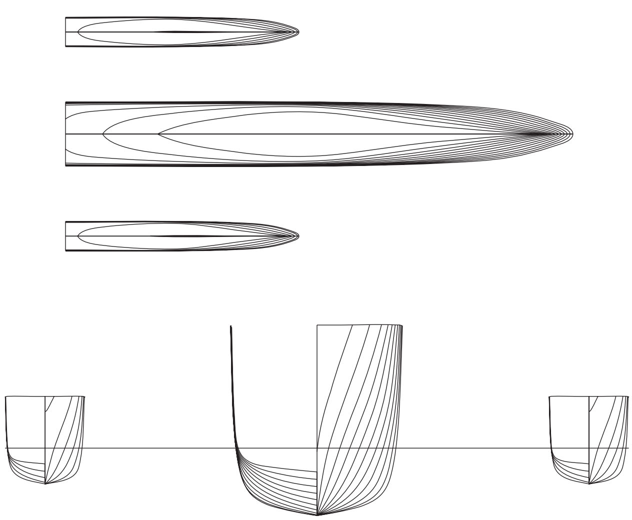

Figure 1 Lines and body plan of trimaran model based on AMECRC Model 9.

with various longitudinal positions of the outriggers are shown in Figure 2 and Table 2, respectively. A pictorial view of the hull is presented in Figure 3.

It may be noted that stagger ratio $r_2/L_1 = 0.0$ implies that the transom of the outrigger is in line with the transom of the centrehull and the stagger of the outriggers is measured from the stern of the centrehull (positive forward). While variation in the transverse separation ratio would have allowed for a more complete analysis, time constraints limited the experimental testing. Hence, a single transverse separation ratio s/L_1 of 0.4, as shown in Figure 2, was tested. It is agreed that the model size is rather small and this may play a major role in resistance determination. However, this is not the case for motions, where the Reynolds number plays an insignificant role.

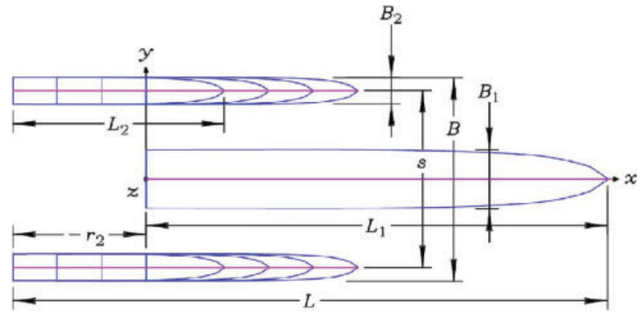

Figure 2 Layout of trimaran indicating the stagger positions.

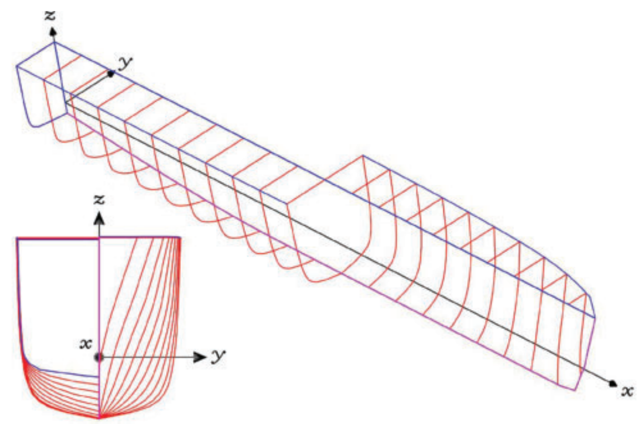

Figure 3 Pictorial view of AMECRC Monohull Model 9.

Test program

Each of the models was tested at Froude numbers of 0.3, 0.4, 0.5 and 0.6. The corresponding carriage speeds were 1.189, 1.585, 1.981 and 2.377 m/s, respectively. The models were also tested in waves of height of 20 and 40 mm. Up to 15 wave frequencies were tested, ranging from 0.4 Hz (2.5 rad/s) to 1.2 Hz (7.5 rad/s) in increments of 0.1 Hz (0.63 rad/s), decreasing to increments of 0.025 Hz (0.16 rad/s) in the vicinity of the resonant peaks. This would provide a smooth plot and allow for cross-checking the results.

There were altogether 32 test conditions with four stagger positions, as shown in Table 2. Only negative sidehull stagger was considered, because it was correctly anticipated that this would reduce motions. In addition, it was known that the resistance would be lower, as shown by Doctors and Scrace (2003). However, the resistance aspect was not studied here. For comparative analysis, an equivalent monohull configuration was also tested.

Model set-up

Because of the lack of experimental investigations with regard to seakeeping of a trimaran hull form, there are few published suggestions governing the values for their radius of gyration. It was decided to set up the pitch radius of gyration of Model 9, with $r_2/L_1 = 0.0$, to the value widely suggested for monohulls, namely, 25% of the overall length. To achieve this, the model firstly had to

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be weighed to determine the amount of ballast required to represent the weight of the hull, which would include the weights and corresponding moments of inertia of the carriage instruments. Once the model was connected to the carriage, the appropriate measuring instruments would then replace these weights.

After the desired pitch radius of gyration for Model 9 with $r_2/L_1 = 0.0$ was achieved, it was decided to keep the ballast mass distribution constant throughout the subsequent stagger configurations.

The result would be a pitch radius of gyration variation between configurations. This was considered more realistic than maintaining the 25% overall length concept for monohulls. This is because, in practice, the location of the outriggers will have an effect on the vessel radius of gyration in pitch and yaw. Even keel was maintained throughout by using independently neutrally buoyant outriggers. These eliminated the need to re-ballast for trim as the sidehulls were moved forward or aft.

For conventional monohulls, it is common practice to assume that the pitch radius of gyration will be similar to the radius of gyration in yaw. Experimental work, however, indicated that this assumption would be inaccurate for a trimaran configuration, where the pitch radius of gyration was, in fact, less than the yaw radius of gyration. While the percentage difference was only around 3%, it was considered important—especially at this early stage of the test procedure—that inaccuracies be minimized. To obtain a true pitch radius of gyration, the bifilar method was employed with the model suspended on its side such that it rotated about its transverse axis.

THEORETICAL METHODOLOGY

Multihull strip theory

The multihull concept is a relatively new development that has introduced additional variables in the prediction of the behaviour of the vessel. This has become a limiting factor for some popular motion prediction computer software. Doctors (1988) has, however, overcome this limitation with HYDROS, a program capable of handling multihull vessels. HYDROS was thus used here for the theoretical motion prediction of the trimaran model. A comparison between the theoretical and experimental results obtained would then provide an evaluation of the capacity of the program to accurately predict trimaran motion characteristics.

Numerical implementation

The HYDROS software uses a sophisticated boundary element method for the computation of the added mass and damping of the ship sections. The method requires the integration of the elementary pulsating source function over both the source and field elements. The result of this is that, as the number of elements is increased, the process rapidly converges. In addition, an artificial 'lid' is applied to the internal free surface of the ship section. Doctors (1988) has explained this in detail. The artificial lid will eliminate any poor behaviour of the calculation resulting from ill-conditioning of the equations near the irregular frequencies.

The actual ship motion theory is based on the strip-theory method of Salvesen *et al.* (1970). Traditionally, limitations of the method include an inability to handle multihull vessels. Enhancements of the method have alleviated this enabling analysis of multihull vessels, which can be achieved in two ways. In the first method, the hydrodynamics of the individual subhulls are considered separately, ignoring any wave interactions. This method is more suitable for high-speed applications where interference will, in practice, be small. Alternatively, for low-speed applications, the strip theory can be applied to all of the subhulls at once. More details of the software were published by Doctors (1993).

RESULTS AND ANALYSIS

Presentation of data

The data obtained from the tank testing was used to produce transfer functions for heave and pitch for each condition tested. The transfer functions produced were nondimensionalised with respect to the wave amplitude for heave and the wave slope amplitude for pitch, as follows:

$$\text{Heave RAO} = A_3/A_0$$

and

$$\text{Pitch RAO} = A_5/k_0 A_0.$$

These were plotted against model-scale wave encounter frequency ω (rad/s), which was nondimensionalised with respect to g and L_1.

The model length used in the nondimensionalisation of encounter frequencies was taken as the waterline length of the centrehull only, which is 1.6 m in this case. This would enable comparative analysis between models while keeping the Froude number constant with respect to length.

In addition, for comparative purposes, a common reference point is required when comparing experimental data. Typically, this point is taken as the LCG of the model. However, the longitudinal shift of the sidehulls produced a variation in the position of the LCG. Analysis about this point would thus result in experimental data that could not be compared. To resolve this, a common reference point was taken as the LCG of Model 9, with stagger position of −0.2. HYDROS, however, is currently coded to calculate the transfer functions with respect to the centre of gravity of the model. Therefore, to enable comparative analysis between the experimental and theoretical results, a reference point at the respective LCG of each model was also required for these investigations. The difference between the results from the two reference points was, however, found to be small, and analysis about both reference points

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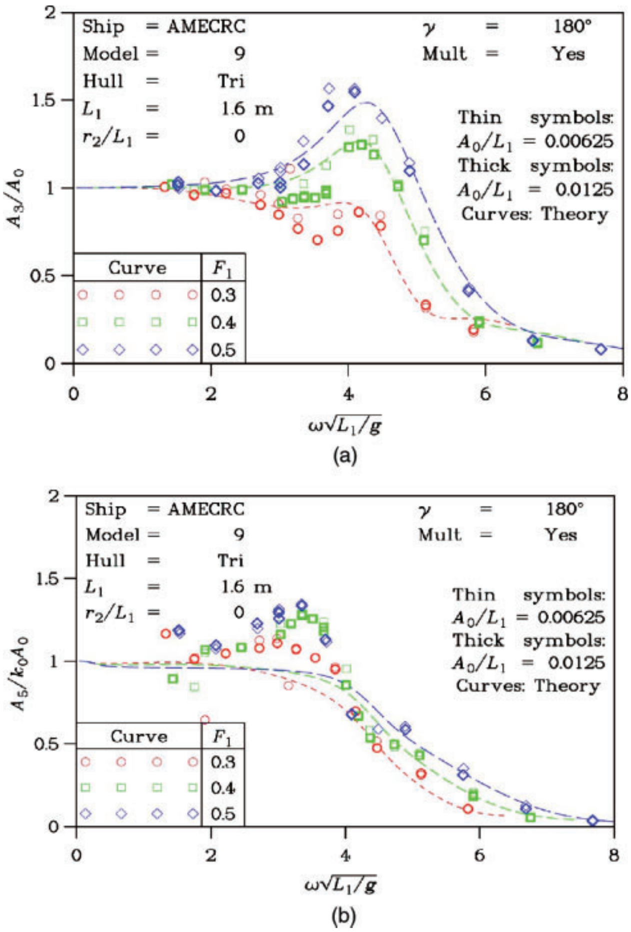

Figure 4 Influence of Froude number on (a) heave for sidehull stagger $r_2/L_1 = 0.0$ and (b) pitch for sidehull stagger $r_2/L_1 = 0.0$.

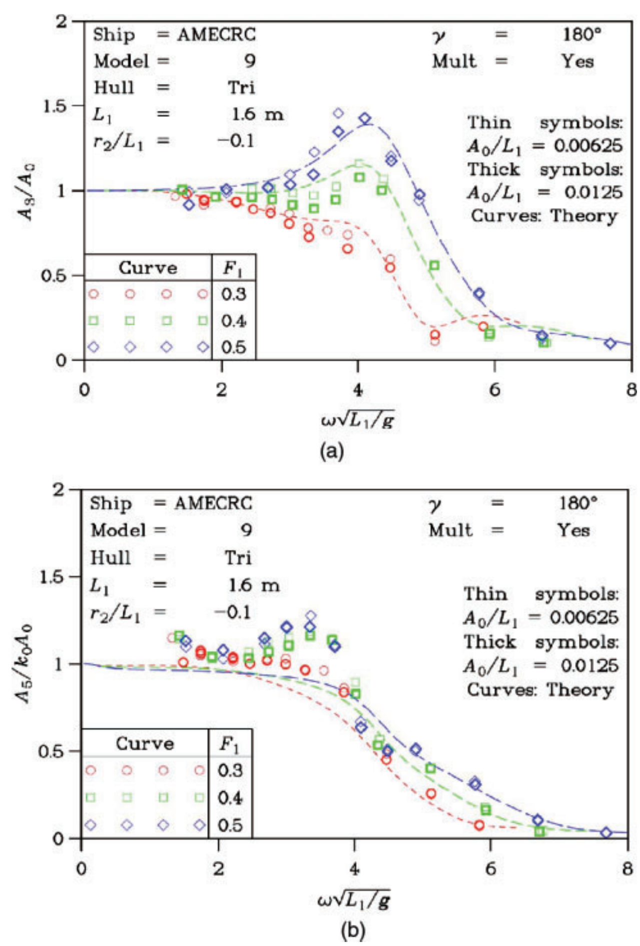

Figure 5 Influence of Froude number on (a) heave for sidehull stagger $r_2/L_1 = -0.1$ and (b) pitch for sidehull stagger $r_2/L_1 = -0.1$.

have, where appropriate, been compared graphically for illustrative purposes.

Data analysis

Figures 4 through 7 display the heave and pitch transfer functions obtained for each stagger position, respectively. Each plot includes the full range of Froude numbers and wave heights indicated earlier in this article. All the results pertain to the case of head seas.

As mentioned, an assumption used by linear strip theory is that above the still waterline, the geometry of the model is irrelevant. This assumption is known as linearity. Theoretical calculations of the exciting and restoring forces thus neglect the effect of variations in the hull form above the waterline—such as hull flare or angled transoms. This would produce similarity in the theoretical transfer functions of a model for different wave heights at a particular Froude number. For certain models, such as those possessing a large degree of flare, this has been found to be inaccurate. Since these models were experimentally tested at two wave heights, the validity of this assumption could be examined.

Figures 4 through 7 illustrate the similarity between the heave and pitch responses of the model, for each of the four stagger positions, at the two different non-dimensional wave amplitudes of 0.00625 and 0.0125 (corresponding to 20 and 40 mm wave heights, respectively). This similarity suggests that, within the range wave heights tested, linearity is a valid assumption for the strip-theory method employed.

Upper flare and the resulting hydrostatic restoring forces and hydrodynamic forces on the seakeeping characteristics of the vessel. The subject trimaran hull form tested incorporates a moderate degree of flare. This will have some small effect on the resulting hydrostatic restoring force as well as the hydrodynamic forces, leading to a modification to the seakeeping characteristics of the vessel. Therefore, the main concern centres on these minor discrepancies in the transfer functions between wave heights, which are apparent around the resonant peaks. This is possibly due to the influence of flare in the bow, which, during immersion, will produce an increasing restoring force. In addition, the nonlinearity illustrated in the graphs could also be related to the emergence of the transom and fore foot at the (greater) 40-mm wave heights. Figure 8 depicts an instant

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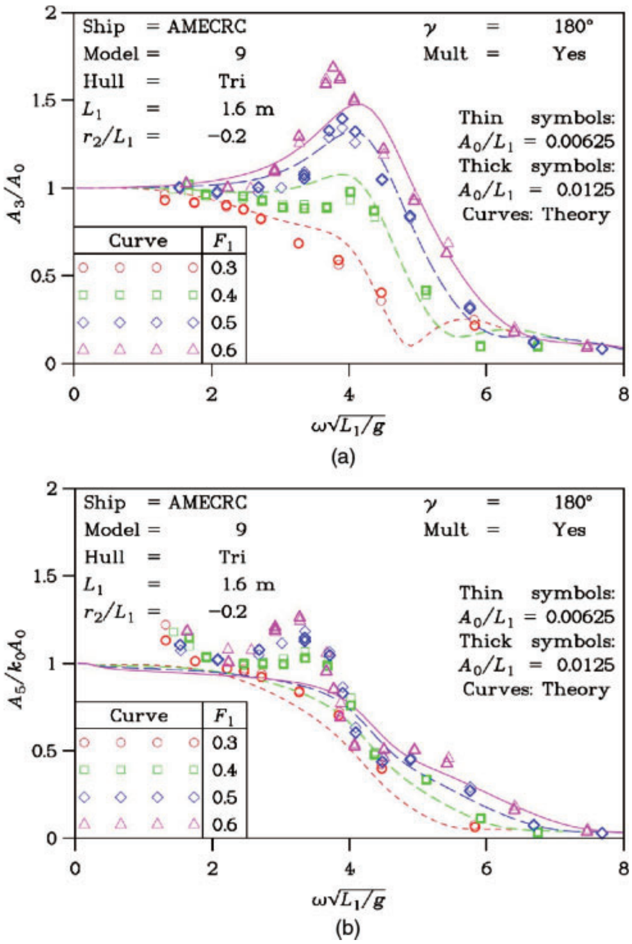

Figure 6 Influence of Froude number on (a) heave for sidehull stagger $r_2/L_1 = -0.2$ and (b) pitch for sidehull stagger $r_2/L_1 = -0.2$.

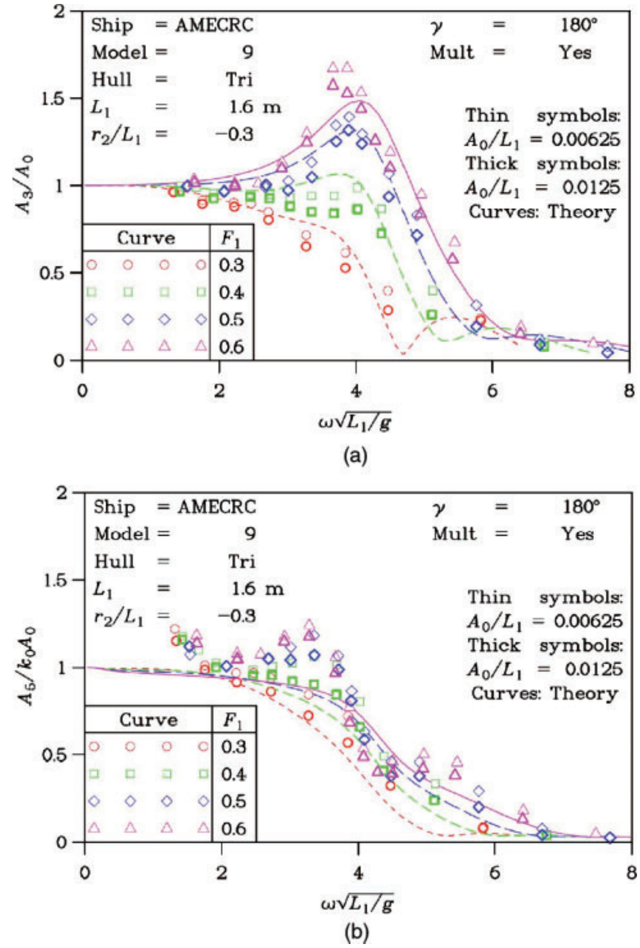

Figure 7 Influence of Froude number on (a) heave for sidehull stagger $r_2/L_1 = -0.3$ and (b) pitch for sidehull stagger $r_2/L_1 = -0.3$.

during the motion where geometric nonlinearities may have been experienced. Fairly close agreement for each Froude number between the two wave heights was, however, expected because of the relatively small difference between the wave heights under consideration.

The response for the monohull is shown in the two parts of Figure 9. In a comparison between the transfer functions of the monohull and the trimaran, it is evident that the magnitudes of the transfer functions for heave and pitch for any of the trimaran configurations are less in comparison with those of the equivalent monohull. In particular, a rapid reduction of the response in pitch directly after the resonant peak, which is more rapid than for the equivalent monohull, is evident. This reduction may be attributed to constructive interference between the outriggers of either incident or reflected waves that could be occurring around the resonant peak. In these frequency ranges, the motion responses in both heave and pitch become significantly less in comparison with the monohull.

This is a significant result, suggesting that a favourable transfer function can be obtained with the addition of sidehulls to a monohull.

Figures 10(a) and (b) show the influence of sidehull stagger more clearly than in the earlier figures. Except in some very small regions of the frequency encounter range, the effect of shifting the sidehulls aft is to dramatically reduce both the heave and pitch motions. This is demonstrated very clearly by the theory, which has the advantage of generating very smooth and easy-to-discern curves. The experiments demonstrate the same point. Of course, the usual scatter in the experimental data makes it more difficult to visually observe this fact from the plots.

Comparison of theoretical and experimental results

Figures 6 through 10 also present a comparison between the results obtained by experimental testing and those obtained theoretically using HYDROS. This provided an indication of the effectiveness of HYDROS to predict the motion characteristics of the trimaran models.

The theoretical motion characteristic predictions for heave correlate very well with the experimental data for all Froude numbers over the entire range of wave encounter frequencies tested. The resonant frequencies and the magnitude of the response in particular have been accurately determined. This suggests that the calculations

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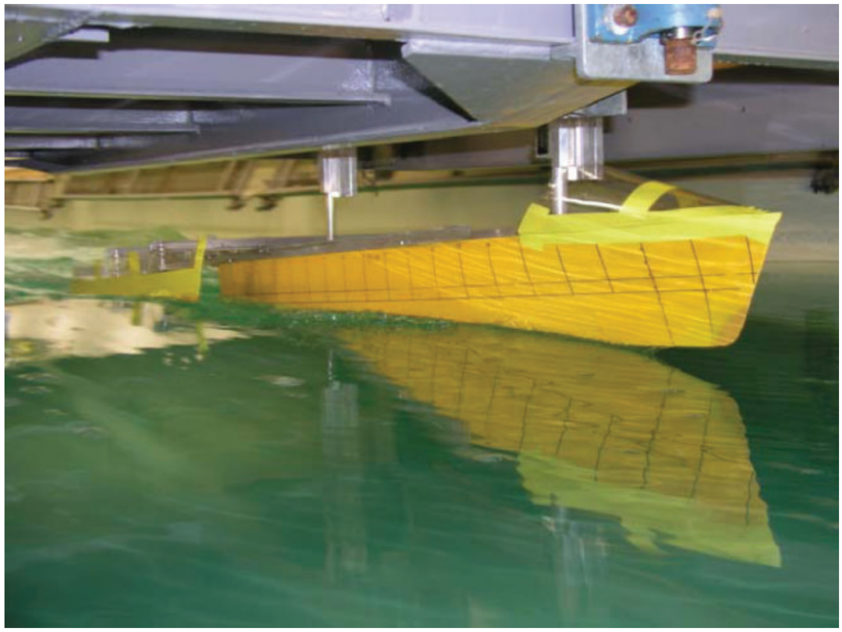

Figure 8 Forefoot emergence of Model 9 at $F_1 = 0.5$ in 40-mm waves ($r_2/L_1 = -0.2$).

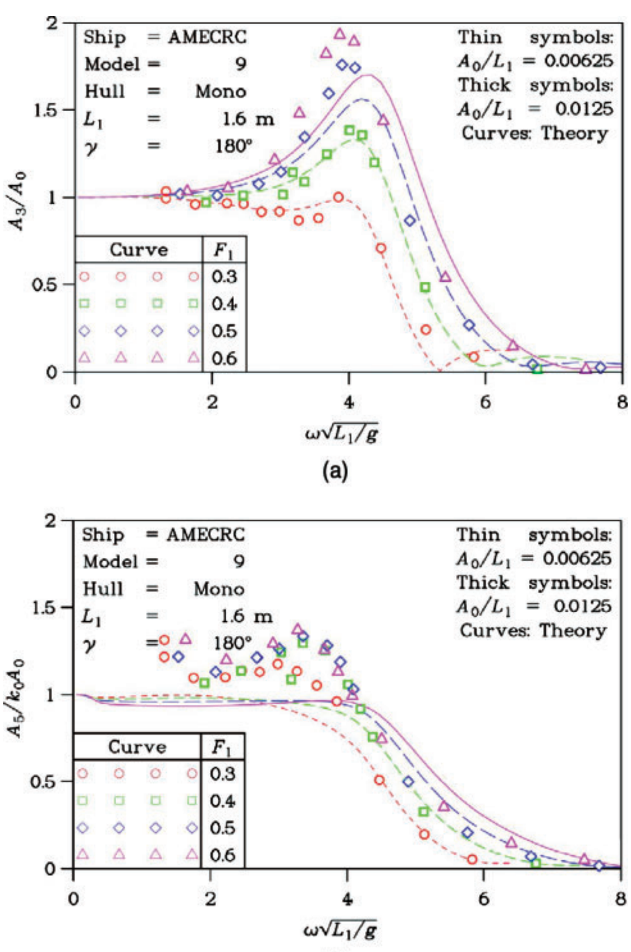

Figure 9 Influence of Froude number on (a) heave of monohull and (b) pitch of monohull.

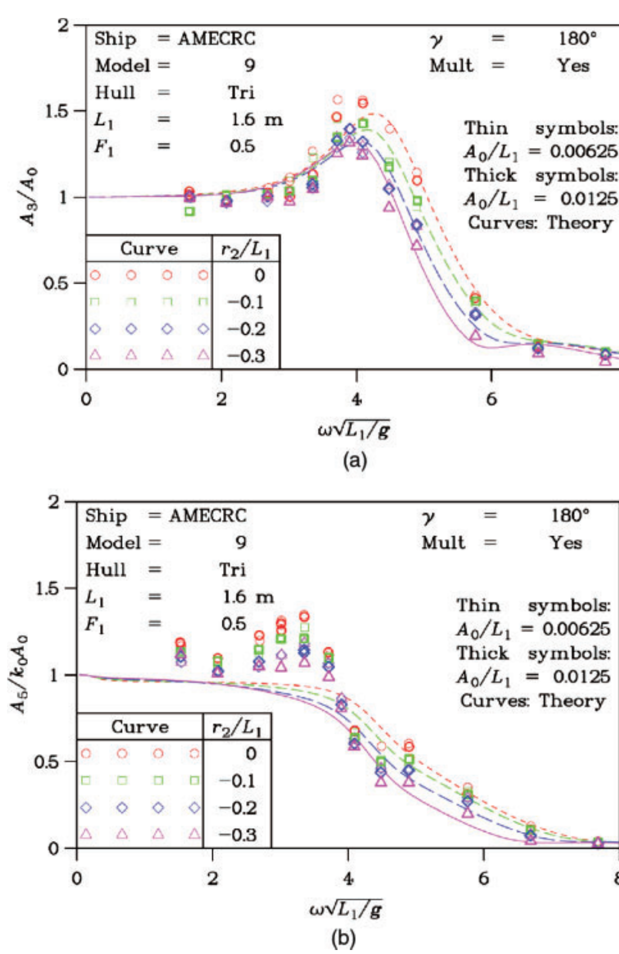

Figure 10 Influence of sidehull stagger on (a) heave for Froude number $F_1 = 0.5$ and (b) pitch for Froude number $F_1 = 0.5$.

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for the added mass and damping and restoring coefficients in heave are valid.

The theoretical predictions made by HYDROS for pitch motion characteristics correlate well with the experimental data, particularly at the higher wave encounter frequencies. The frequency at which resonance occurs has been accurately predicted by HYDROS. However, the magnitude of the resonant response has been significantly underestimated.

CONCLUSIONS

The experimental analysis suggested that the position of the trimaran outriggers will have a significant effect on vessel motion characteristics. It was found that response magnitudes for both heave and pitch decreased with aftward shifts in the outrigger position. This trend was consistent over the range monohull would have a reducing effect on the motion characteristics of the vessel. This effect on seakeeping performance could be attributed to either the increase in the pitch radius of gyration associated with longitudinal shifts of the outriggers towards the aft or the different hydrodynamic interference effects for each configuration of longitudinal spacings.

Furthermore, it is recognised that the shifts in the longitudinal position of the sidehulls produced an increase in the overall length of the model. While a model length was not required for the nondimensionalisation of the heave or pitch RAOs, nondimensionalisation of the wave encounter frequency did require a value for the model length. For comparative purposes, this length was taken as the (constant) waterline length of the centrehull (1.6 m) for all models tested. The point here is that the plots would appear differently if one instead used the (variable) overall model length for the purpose of nondimensionalisation.

The comparison of the results obtained experimentally and theoretically has shown that there is significant validity in using appropriate theoretical methods in order to reduce resources spent in design. Theoretically obtained wave-induced motion characteristics were found to correlate well with those obtained experimentally for each model over the range of Froude numbers tested. This correlation was particularly evident for heave motions, while those for pitch were generally underestimated near resonance.

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